

The Silver Valley Lead Study: The Relationship between Childhood Blood Lead Levels and Environmental Exposure

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This paper is directed to those persons concerned with the relationship between blood lead levels and environmental exposures to lead. Information presented in this paper represents one of the largest collections of epidemiological data relating blood lead levels to environmental exposures. The observed annual average ambient air lead concentration ranged from approximately $0.5 \mu\text{g Pb}/\text{m}^3$ to $23 \mu\text{g Pb}/\text{m}^3$, while lead in soil ranged from 50–24,600 ppm. Blood lead levels of children (ages 1–9 years) are related to a host of environmental variables via regression techniques. Blood lead levels were found to be most influenced by five variables. These variables are: ambient air lead, soil lead, age of the child, dustiness of the home, and occupational status of the parents. It is concluded, based upon the results of this study, that any environmental control strategy should address both the air and the soil. Soil levels in excess of 1000 ppm lead as well as air lead levels greater than $2 \mu\text{g Pb}/\text{m}^3$, 30 day average, were found to be unacceptable.

In early 1974, evidence of excess lead intoxication surrounding a lead smelter in northern Idaho became apparent. An extensive study of both the inhabitants and the environment of the affected area was undertaken. Over 2000 blood lead samples were drawn from children in the area and more than 50,000 pieces of allied medical and environmental data were obtained.

In the case of human exposure to lead, a large volume of evidence exists that relates excess levels of Pb in the blood to adverse health effects. However, the current literature does not adequately address the relationship between exposures and blood Pb levels. It is the intent of this paper to establish

a relationship between observed blood Pb levels in children and observed ambient concentrations of Pb. The existing health standard for blood Pb levels can then be used in conjunction with this relationship in order to establish ambient standards for Pb.

Environmental quality standards should be designed to protect susceptible subgroups of the population fully. In the case of Pb, children are both most susceptible and are at a higher risk. Barltrop, *et al.*¹ studied children and their mothers living in two different towns with differing soil Pb concentrations. The study revealed that the blood Pb levels of the children were higher than that of their mothers in both cities. Landrigan, *et al.*² found a strong inverse relationship between blood Pb levels and age among people living in the same area near a smelter in Texas. High blood Pb levels are a health risk to the nervous system. The major development of a child's nervous system takes place during his first four years. This age group represents the highest risk group. Thus, it is imperative that any ambient lead standard be designed to protect young children.

In order to establish an environmental quality standard for Pb based on maintaining normal blood Pb levels, two relationships must be demonstrated: 1) a relationship between adverse health effects and greater than normal blood Pb levels; and 2) a relationship between blood Pb levels and ambient Pb levels. The relationship between adverse health effects and blood Pb levels has been extensively studied. In recent years, the upper limit of what is considered a "normal" or acceptable blood lead has been decreasing. David³ has suggested an upper level of $24.5 \mu\text{g Pb}/100 \text{ ml}$ while Angle and McIntire⁴ have stated that the present acceptable level is no longer tenable. However, new levels have neither been established nor gained universal acceptance. For this reason, the established limit of $40 \mu\text{g Pb}/100 \text{ ml}$ and above will be used as indicative of undue Pb absorption for the purposes of this paper. If new medical studies demonstrate that this limit should be modified, the procedures can be simply redone for the new level.

Method

A survey to ascertain the prevalence of increased Pb absorption among children living near a primary Pb smelter in northern Idaho was taken among 1149 children 1 to 9 years old during August, 1974. Blood Pb samples were obtained in conjunction with a series of environmental samples, social and medical histories, and general observations of the home environment. A follow-up study of 781 children was conducted in August 1975 to ascertain the change in blood Pb levels that may have resulted from altered environmental and social conditions.

Five study areas and two control areas were defined. The five study areas were arranged concentrically about the smelter with AREA I consisting of homes within 1 mile of the smelter, AREA II within 1 to 2½ mi, AREA III within 2½ to 6 mi, AREA IV within 6 to 15 mi, and AREA V within 15 to 20 mi. AREA VI is a rural town 45 mi northwest of the smelter. The principal industry in Area VI is logging, and because it had no history of Pb mining activity, it was established as the primary control area. AREA VII is a side valley to the southwest of the smelter that had been the site of previous Pb mining activity and can receive a small amount of atmospheric contamination from the smelter.

A series of environmental samples were collected at each home where a blood sample was obtained. These samples consisted of composite surface soil, inside and outside house dust, inside and outside paint, grass, and certain garden vegetables. The procedure has been previously described by Yankel and von Lindern.⁶

Ambient air Pb levels were measured by 9 hi-volume air samplers stationed throughout the Silver Valley. These samplers were operated for 24 hr every other day. Since many of the subject children lived between monitors, it was necessary to develop a model capable of predicting ambient levels between monitors. A highly significant relationship between distance from the smelter and ambient Pb concentration was found. The relationship was used to estimate the ambient air Pb level for various locations in the valley.

A brief medical history was taken for each child. This history consisted of age, sex, length of residence at current and previous address, history of pica, history of blood Pb testing, and the occupation and education of parents. General observations were made of the home environment that included categorizing the age of the home, type of home exterior, condition of exterior paint, percent vegetation cover, cleanliness of the interior home, amount of visible dust present inside the home, and the condition of the inside paint.

Results

In the August 1974 survey, 99% of the 1 to 9 yr old children living within 1 mi of the smelter were found to have levels in excess of 40 µg Pb/100 ml. The frequency of abnormal Pb absorption was found to decrease with increasing distance from the smelter. Following the announcement of these results, certain emergency measures were initiated to reduce the risk of Pb intoxication. These measures included: chelation of children over 80 µg Pb/100 ml, purchase and destruction of as many homes as possible within ½ mi of the smelter, distribution of "clean" soil and gravel to cover highly contaminated areas, initiation of a hygiene program in the schools, and reduction of ambient air Pb levels through reduction of smelter emissions. A follow up survey in August 1975 revealed that the blood Pb levels had decreased. Figure 1 shows the percentage of children, by area, who had blood Pb levels of 40 µg Pb/100 ml or more in the August 1974 and 1975 surveys.

The mean Pb levels found in the ambient air and soil decreased with increasing distance from the smelter, following much the same pattern as that of blood Pb levels. The values

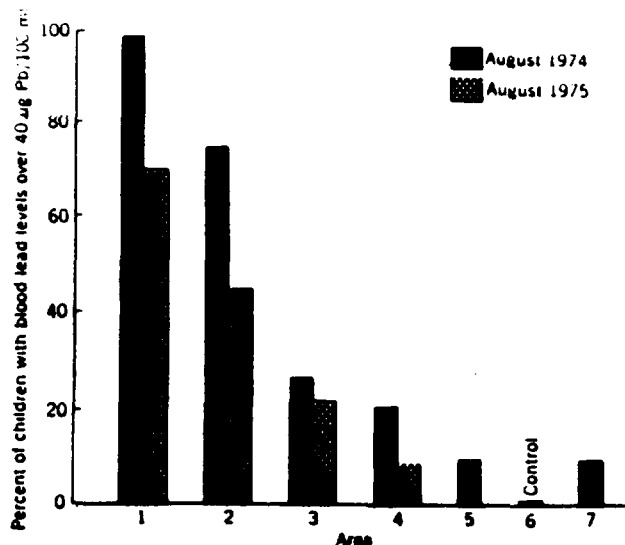


Figure 1. Percent of children, by area, that had blood lead levels of 40 µg Pb/100 ml or over in Aug. 1974 and Aug. 1975.

for the ambient air are shown in Figure 2. These values are averages for the 12 month period prior to the 1974 and 1975 surveys. Figure 3 shows the mean soil value, by area, found in the two surveys. Tap water was sampled for Pb and found to be within established standards.

Correlation coefficients were run for all environmental and medical variables for each child in the 1974 survey. Blood Pb levels must closely correlate with the ambient air Pb ($r = 0.74$) and soil Pb ($r = 0.54$). A correlation matrix is shown in Table I.

Multiple regression analysis of all the August 1974 and 1975 data indicates that 5 factors significantly ($p < 0.0001$) influenced the probability of a child experiencing an excess blood Pb level:

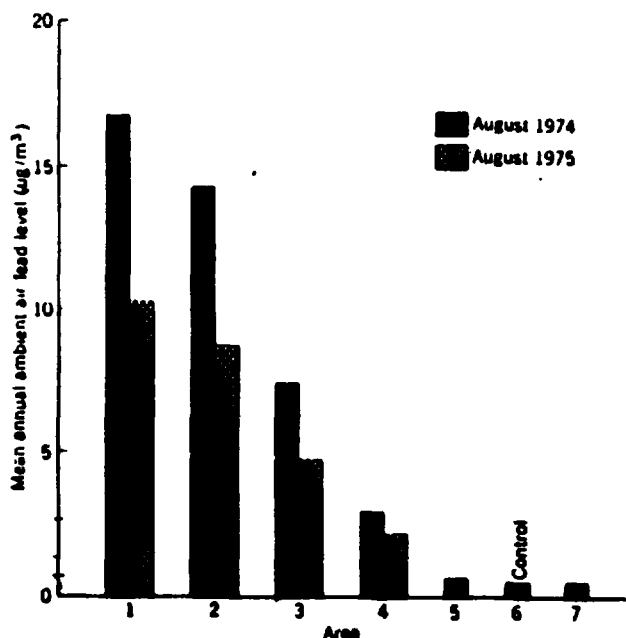


Figure 2. Annual ambient air lead concentration, by area, prior to the August 1974 and August 1975 surveys.

1. Ambient air lead concentration.
2. Lead concentration of the soil.
3. Age of the child.
4. The cleanliness of the home.
5. The occupation of the parent as defined by Hollingshead.⁶

Other variables were examined. Most were non-significant in explaining blood Pb levels. Lead levels in inside paint were found to have a slightly negative correlation with blood Pb levels. Sex was found to have no significant effect. Pica was found to have a slight correlation with blood Pb. However, because sampling bias was evident among the interviewers, the results concerning pica are questionable. Two variables describing the occupation of the head of the household were considered. One was the place of employment and the other, the Hollingshead⁶ occupational variable. Both were of similar significance and had nearly the same effect when added to the regression equation. The Hollingshead⁶ variable was selected for use in the final regression model because it was more indicative of social status and because the employment variable was poorly distributed geographically.

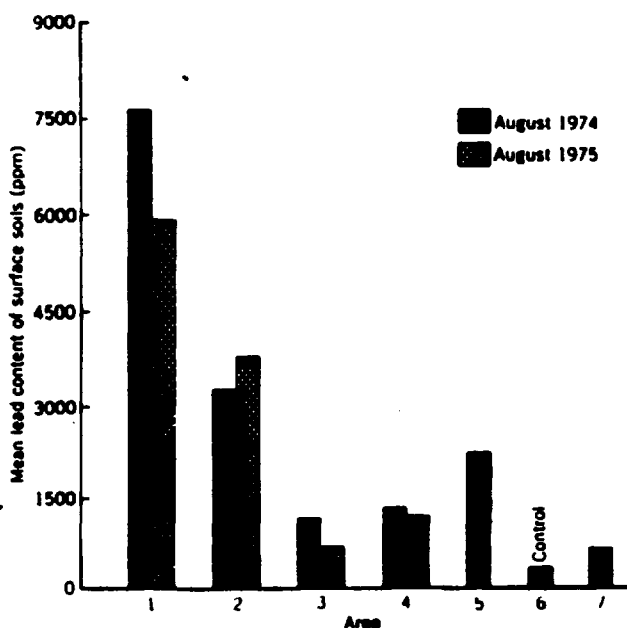


Figure 3. Average surface soil, by area, for each child tested in the 1974 and 1975 surveys.

Discussion

The ambient air Pb level is the strongest independent variable in describing blood Pb levels. It is evident that the air Pb level is the factor that most contributes to excess absorption in this study. Air exposure alone explains 55% of the variance in blood Pb levels.

The soil Pb level was also a highly significant variable. Air and soil Pb together explain 58% of the variance in blood Pb levels. Barltrop⁷ studied 2 year old children living in several areas with low ambient air Pb concentration (mean monthly averages from 0.28 to 0.34 $\mu\text{g Pb}/\text{m}^3$). The study groups were divided according to soil Pb concentration: <100 $\mu\text{g/g}$, <10,000 $\mu\text{g/g}$, and >10,000 $\mu\text{g/g}$. The resultant mean for each group showed a geometric mean blood Pb from 20.7 $\mu\text{g Pb}/100\text{ ml}$ in the low soil Pb group, to 29 $\mu\text{g Pb}/100\text{ ml}$ in the high soil Pb group. The data suggest that although a definite relationship

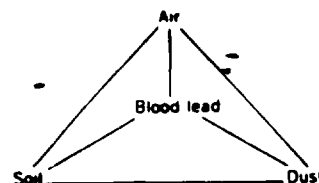
Table 1. Correlations (simpler) between Ln (blood lead) and five independent variables, 1974 data, $N = 879$

	Ln (Blood Lead)	House dust- ness	Soil	Age	Occu- pation	Air
Ln (Blood Lead)	1.00	0.21	0.54	-0.16	0.14	0.74
House dustiness		1.00	0.18	0.01	0.27	0.05
Soil			1.00	-0.05	0.05	0.52
Age				1.00	-0.02	-0.07
Occupation					1.00	0.03
Air						1.00

exists, soil Pb levels alone, within the wide range studied, would not greatly influence the probability that a child would have a blood Pb level greater than 40 $\mu\text{g Pb}/100\text{ ml}$.

Although air Pb levels are the most significant factor in explaining excess blood Pb levels, it is not correct to attribute the total effect to direct inhalation. Another source of exposure to Pb is house dust that can result from air and soil contamination. Landrigan, *et al.*² measured the concentration of Pb in air, soil, house dust, and blood near a smelter in El Paso, Texas. In the area of greatest exposure he found a significant relationship ($p < 0.05$) for blood Pb levels versus soil Pb and a highly significant relationship ($p < 0.0001$) for blood Pb levels versus house dust Pb. Lepow, *et al.*⁸ has measured the concentration of Pb in household dust and soil as well as the concentration and amount of Pb found on the hands of 22 children. After observing these children during normal play, Lepow stated, "It is quite possible for a young child who is frequently putting his hands in his mouth during play, in a heavily leaded environment, to ingest excessive quantities of lead and accumulate an increased body burden of lead."

The importance of air, soil, and house dust as sources of exposure to ambient Pb suggest the following model.



The importance of house dust as a route of exposure is supported by the other factors found to influence the probability of a child having an excess blood Pb level. The role of Pb in dust depends on both the concentration of the Pb and the availability of the dust. Each home that was visited in this study was judged as to the amount of dust available. The scale was simply clean, moderate, or dusty. This variable was found to be quite significant in explaining the variance in blood Pb levels. Table II shows the mean blood Pb level by area and home dustiness. Blood Pb levels are significantly higher in the dirtier homes in areas subject to high ambient exposures.

The concentration of Pb in house dust samples obtained from vacuum cleaner bags did not significantly correlate with blood leads. Little importance, however, is attached to this result. This sampling technique provides for little quality control. Nearly half the homes in the study had no vacuum cleaners or samples were not available. The amounts of extraneous material in the samples also varied greatly. This made consistent laboratory analyses quite difficult.

Table II. Observed mean blood lead level based upon area and cleanliness of home ($\mu\text{g Pb}/100\text{ ml}$).

Area	Clean home	Moderate home	Dirty home
Area I	39	67	77
Area II	44	50	52
Area III	33	36	33
Area IV	30	33	39
Area V	26	29	36
Area VI	20	22	22
Area VII	26	31	39

Age also tends to play a modifying role with regards to a child's blood Pb level. As demonstrated by Table III, the mean blood Pb levels for children follow the same age-dependent pattern in all areas. The blood Pb levels of the children generally decrease with age. This decrease corresponds with reduced mouthing activity in older children. A notable exception to this trend can be consistently found in the 1 year olds where reduced mobility, and thus reduced access to Pb, may tend to play a modifying role. Accounting for this inconsistency in the analysis of the data did not result in a significant change in the results.

The occupational status of the parent, as defined by Hollingshead,⁶ was also found to play a modifying role on the blood Pb level of children. This variable is considered to be an indicator of social status, and, as such, may reflect personal hygiene to some extent.

Multiple regression analysis was performed in order to obtain the best data fit for the 5 variables cited above. The model shown below is based upon analysis of Areas I-VI for the 1974 data set. ($n = 879$, $R^2 = 0.62$, $p < 0.0001$). Area VII was not included because the air Pb levels could not be accurately predicted.

$$\ln(BPb) = 3.1 + 0.041(A) + 2.1 \times 10^{-5}(S) + 0.087(D) - 0.018(Y) + 0.024(E)$$

where BPb = blood lead level— $\mu\text{g Pb}/100\text{ ml}$

A = ambient air lead— $\mu\text{g Pb}/\text{m}^3$

S = soil lead—ppm

Y = child's age—years

D = dustiness of home—integer (0, 1, or 2)

E = Hollingshead⁶ occupational variable—dimensionless

By assuming selected values for the independent variables, this model can be used to predict the mean blood levels of a subject population. Table IV shows the predicted mean blood Pb level for children assuming typical values for the non-source (modifier) variables. (Age = 5, moderately clean home, and average occupation.)

In the development of environmental health criteria, it is important to consider the dose-response relationship of a subject population. The dose-response relationship of this population can be seen in Table IV. That relationship is logarithmic, a one unit increase in air exposure ($\mu\text{g Pb}/\text{m}^3$) will result in more severe increases in blood Pb levels as exposures

and blood Pb levels increase. In this study, the ratio of blood Pb increase per unit air Pb exposure increase was 1.1:1 at 0-1 $\mu\text{g Pb}/\text{m}^3$ air Pb exposure and increased to 2.1:1 at the highest exposure levels (17-18 $\mu\text{g Pb}/\text{m}^3$).

It is important to remember that these numbers represent the mean dose-response relationship of the population. Some individuals will respond less severely, others more severely. Those that respond more severely represent the most susceptible portion of a population. It is those individuals that are of greatest concern in establishing health protection standards. Some method of considering the dose-response relationship of these most susceptible persons must be developed.

Table IV. Predicted mean blood lead level for various air and soil exposures using typical values for non-source variables (age = 5 years, home cleanliness = 1, and occupation = 4).

Air $\mu\text{g Pb}/\text{m}^3$	Soil (ppm Lead)		
	500	1000	5000
1	26.7	27.0	29.3
2	27.8	28.1	30.5
3	29.0	29.3	31.8
4	30.2	30.5	33.1
5	31.5	31.8	34.5

Methods demonstrated by Schubert, *et al.*⁹ can be used to quantify this dose-response relationship. They suggest that any population subjected to uniform exposure of a trace element will exhibit a response that is log-normally distributed. Moreover, those distributions in populations subjected to different ranges of exposure will exhibit the same geometric standard deviation. Analyses of the data in this study show that the blood Pb levels follow a log-normal distribution for all areas and that all areas exhibit nearly the same geometric standard deviation. The geometric means and standard deviations are given in Table V.

The log normal distribution has the following characteristics:

$$Mg \cdot Sg^n = Dn$$

where:

Mg = geometric mean blood lead level

Sg = geometric standard deviation

n = the number of standard deviations

Dn = values of the blood lead at n standard deviations.

This equation can be used to show that the dose-response ratio at +n standard deviations will be Sgⁿ times the mean response. In that way, the dose-response relationship can be quantified at any percentile of the population.

However, what is most important to those concerned with standard setting is the percentage of the population that will

Table III. Geometric mean blood lead levels for 1974.

	Age Group										
Area	1	2	3	4	5	6	7	8	9	Teenage	Adult
I	59	72	75	75	68	66	63	60	57	39	37
II	50	51	55	46	49	50	47	42	40	33	33
III	33	36	36	35	35	35	31	32	32	28	30
IV	31	35	34	31	31	35	30	32	30		34
V	27	35	29	29	29	28	25	27	24		32
VI	21	25	22	23	20	22	20	22	17		
VII	28	30	28	32	30	26	37	30	20	35	32

Area	Children (Aug 74)			Teenagers (Oct 74)			Adults (Oct 74)		
	BPb	Sg	n	BPb	Sg	n	BPb	Sg	n
I	65.6	1.33	179	39.3	1.26	20	37.7	1.32	83
II	47.4	1.30	204	33.3	1.23	38	32.6	1.33	192
III	33.8	1.26	193	27.9	1.40	24	29.7	1.35	49
IV	32.3	1.29	168			1			5
V	27.6	1.33	198			0			3
VI	21.0	1.32	92			0			0
VII	30.3	1.25	40	34.6	1.31	14	32.3	1.30	42

exceed a particular blood Pb level. The characteristics of the log-normal distribution can be used to determine that percentage directly. Specifically, for any given mean blood Pb level, the percentage of the population that will have blood Pb levels exceeding $40 \mu\text{g}/100 \text{ ml}$ can be determined.

For this study, Sg was found to have a value of 1.3, $1/n$ is the maximum permissible blood Pb level ($40 \mu\text{g}/100 \text{ ml}$), and Mg is determined by the regression model. Selected values for Mg are found in Table IV. By substituting these selected values of Mg and solving for "n" in the above equation, the number of standard deviations between the mean and $40 \mu\text{g Pb}/100 \text{ ml}$ can be determined.

Using standard statistical tables, the value of "n" can be used to determine the percentage of the population predicted to have blood Pb levels in excess of $40 \mu\text{g Pb}/100 \text{ ml}$. These percentages are found in Table VI and correspond to the mean blood Pb levels found in Table IV.

Table VI. Percent of children expected to exceed a blood lead level of $40 \mu\text{g Pb}/100 \text{ ml}$ for various air and soil exposures using typical values for non-source variables (age = 5 years, home cleanliness = 1, and occupation = 4).

Air $\mu\text{g Pb}/\text{m}^3$	Soil (ppm Lead)		
	500	1000	5000
1	6	7	12
2	8	9	15
3	11	12	19
4	14	15	24
5	18	19	29

Conclusions

This study and others show that excess ambient air Pb levels can result in abnormal absorption in both children and adults. It seems that the mechanisms of absorption differ greatly between the two groups. Children represent the highest risk group and standard setting should be addressed to them. The total impact of ambient air contamination on children is due to both their physiological characteristics and habits. Normal childhood habits include the active ingestion of small amounts of soils and dust that contain particulate deposited by polluted air. Any environmental control strategy devised for Pb should take into account all routes of exposure that significantly contribute to excess Pb absorption. The strategy must not only address the lungs of the child, but the environment in which he lives. In this study, five factors (air,

soil, dust, diet, and occupation) were identified as influencing blood Pb absorption. Two of those factors, air and soil contamination, can be regulated by environmental control. The other factors cannot be controlled by regulations.

When setting a standard, a subjective decision must be made as to what percentage of the population should be allowed to exceed the $40 \mu\text{g Pb}/100 \text{ ml}$ level. A second decision must be made as to what combination of air and soil limitations shall be applied to achieve that end. Based on the results of this study, it is apparent that soil levels in excess of 1000 ppm Pb or air levels in excess of $2 \mu\text{g Pb}/\text{m}^3$, 30 day average, will result in excessive percentages of children exceeding the $40 \mu\text{g Pb}/100 \text{ ml}$ blood Pb standard.

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